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SHORT COMMUNICATION

THERMAL RESPONSE CHARACTERISTICS OF STONE: IMPLICATIONS FOR WEATHERING OF SOILED SURFACES IN URBAN ENVIRONMENTS

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ABSTRACT

Soiling of stone surfaces by particulate deposition increases absorption of radiant energy, raises surface/subsurface temperature gradients and accentuates rates of surface temperature change. Short-term fluctuation of raised surface temperatures, in response to variations in windspeed and cloud cover, may ultimately contribute to stone breakdown through 'fatigue' effects which reduce cohesive strength of intergranular bonds and initiate microfracture development. The effects of soiling are particularly marked for stone with low thermal conductivity and high albedo when clean. Albedo change has implications for the effectiveness of weathering processes and the durability of building stone by creating microenvironmental conditions which are more severe than those indicated by macroenvironmental regimes.

KEY WORDS albedo; 'fatigue' effects; insolation; salt weathering

INTRODUCTION

Soiling of buildings and monuments is a major problem directly attributable to past and present fossil fuel combustion from vehicular, industrial and domestic sources. While soiling is unsightly, it may also have serious implications for stone durability as phenomena such as granular disintegration, blistering and scaling are often found associated with surface discoloration (Smith and Magee, 1990).

On light-coloured stone, crusts and stains effectively reduce albedo which may increase solar energy absorption and hence surface temperature. Because of the spatial variability of stone soiling (Figure 1) adjacent 'clean' and 'soiled' surfaces may, therefore, experience quite different surface temperature conditions which in turn may influence the nature and effectiveness of decay.

Surface and near-surface temperature variations are important because they affect precisely the zone in which many weathering mechanisms, responsible for physical breakdown, are concentrated. The nature of these temperature regimes depends not only upon albedo, but also on other lithologically variable thermal characteristics such as thermal conductivity and specific heat capacity (McGreevy, 1985). In addition to these thermal properties, temperature response is also controlled by a hierarchy of insolation cycles and fluctuations. The most obvious of these are diurnal fluctuations, but evidence from natural environments indicates that stone surface temperatures also fluctuate over much shorter time periods (*c.* 15 min) in response to factors such as variations in windspeed and cloud cover (Whalley *et al.*, 1984; Jenkins and Smith, 1990). Such short-term fluctuations are particularly intense under relatively 'clear sky' conditions when ambient air temperatures are low (Hall and Hall, 1991) and specifically affect the near-surface zone of maximum decay.

Any factors which alter thermal response in this zone must influence stone susceptibility to various

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Figure 1. Spatial variability of building stone soiling in an urban environment. This picture shows part of the inner court of the City Hall in Belfast, Northern Ireland, where soiling is best developed on surfaces infrequently exposed to rainwash

weathering mechanisms and subsequent rates and patterns of decay. In the light of these comments this study examines, under controlled laboratory conditions, the effect of albedo change caused by surface soiling and implications of this for stone decay under a regime of rapidly fluctuating surface temperatures.

METHODOLOGY

Materials

Four rock types are used: Portland limestone, Dunhouse sandstone, Baumberger sandstone and Pentellic marble. Each has different structural and mineralogical properties but all exhibit similar light-coloured surfaces (high albedo) when clean (Table I). Three 50 mm cubes of each rock type were cut for use during the simulation.

Surface soiling

Natural stains and crusts are a mixture of organic and inorganic airborne material (pollen, flyash and dust), inorganic precipitates (salts) and biota (fungae and bacteria) (Whalley *et al.*, 1992). To simulate these conditions blocks were treated with either a thin dusting of oil flyash or coal flyash while one block from each lithology was kept clean as a control sample. The simulations specifically replicate thin crusts/stains on buildings and not thick accretions which can develop in sheltered sites.

Oil flyash came from Ballylumford Power Station, Co. Antrim and comprises perforated cenospheres mostly $< 100\,\mu m$ in diameter (Figure 2a). Coal flyash was from Kilroot Power Station, Co. Antrim and is made up of much smaller siliceous spheres (Figure 2b). Flyash was fixed to the stone surfaces using a

Table I. General characteristics of rock types used in simulation experiment

Rock type	Munsell colour notation (dry) and colour description	Porosity (%)	General description
Portland limestone	2.5Y 8/1 (greyish white)	17·90*	Oolitic limestone with bimodal pore size distributions
Dunhouse sandstone	10YR 7/2 (light grey/ very pale brown)	18·10†	Non-calcareous fine to medium grained sandstone with interstitial kaolinite deposits
Baumberger sandstone	10YR 7/2 (light grey/ very pale brown)	21·40‡	Fine grained calcareous sandstone
Pentellic marble	N8 (white)	0·18§	Dense white marble

* McGreevy (1982)
† Leary (1986)
‡ Sabbioni *et al.* (1992)
§ Touloukian *et al.* (1989)

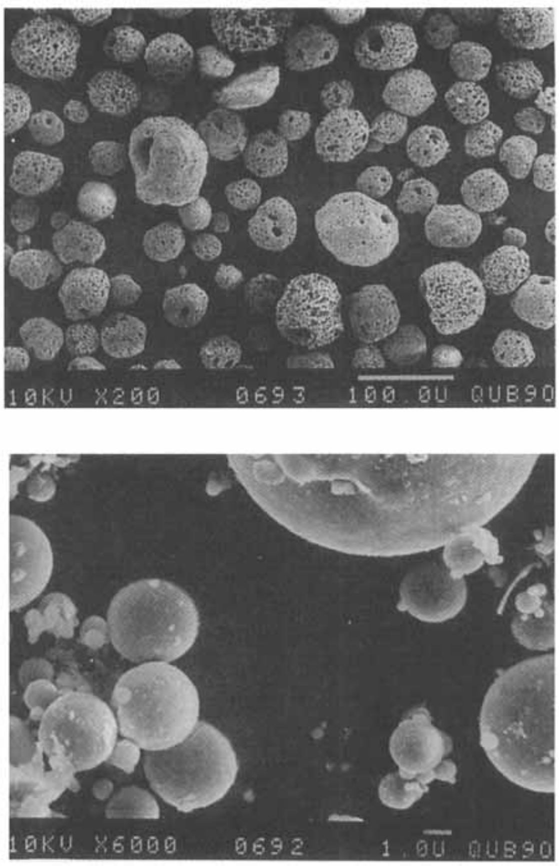
(a)
(b)


Figure 2. (a) Scanning electron micrograph of oil flyash particles which comprise perforated cenospheres generally < 100 μm in diameter (scale bar 100 μm). (b) Scanning electron micrograph of coal flyash particles comprising siliceous spheres (scale bar 1 μm)

petroleum-based aerosol adhesive ('Spray Mount'). Oil flyash formed a black (10YR 2/1) surface layer whereas coal flyash formed a light grey (10YR 7/2) surface.

Experimental procedure

The equipment used simulates direct heating of stone samples and short-term temperature fluctuations (Figure 3). It consists of a large drum 75 cm in diameter and 100 cm deep. Three ports located at regular intervals around the circumference of the drum allow access to the interior and three infrared heat lamps fixed over the drum provide the heat source. Interruptions to this heat source are achieved by a rotating semi-circular blade driven by a 'stepping motor' which can be set to revolve at different speeds ranging from a minimum of 1 rev/8 h to a maximum speed of 16 rev/h. When, for example, the blade is set to rotate at 2 rev/h any stone samples below will experience two shade episodes, each of 15 min duration, in every hour.

Direct heating with infrared lamps more accurately replicates 'natural' conditions where thermal properties determine temperature response characteristics of different lithologies. When all three lamps are fully on they create a relatively stable air temperature within the drum of 40°C. These are subsequently referred to as 'warm air' conditions and represent, for example, central European and Mediterranean summer regimes. The attachment of a fan and cooling unit to one of the access ports reduces air temperature within the drum by approximately 15°C. These are subsequently referred to as 'cool air' conditions and reflect typical summer temperatures experienced in many temperate environments.

Temperature measurement

Air and rock temperatures were recorded at one minute intervals using a 12-bit Grant Instrument Squirrel Logger and bead thermistors. Blocks were prepared by drilling a hollow approximately 1 mm deep in the upper block face and by drilling 25 mm up from the centre of the block base. Two bead thermistors were used for each block – one secured to the surface in the shallow hollow using a non-silicone heat transfer

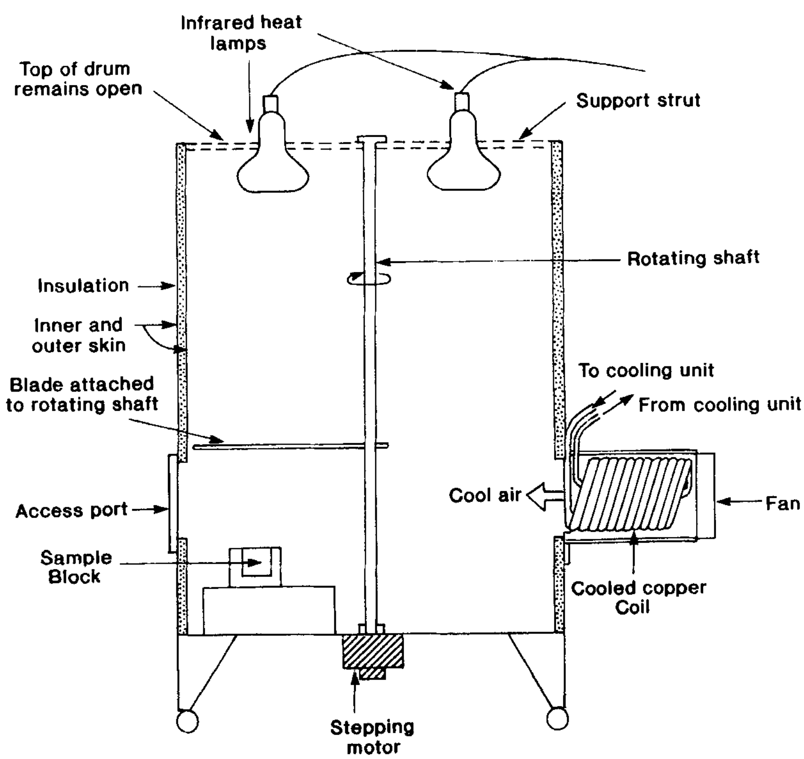


Figure 3. Detail of circular drum used in simulation experiments with the optional air cooling unit attached

compound and the other inserted into the base, after which the hole was tightly packed with powdered rock and plugged with cotton wool. Each block was then embedded in a jacket of expanded polystyrene leaving only one exposed face (Figure 4). Insulating small blocks and restricting heat loss/gain to only one surface replicates conditions experienced on larger stone surfaces.

Another bead thermistor to measure air temperature was positioned just above the block surfaces and shaded by a small foil canopy which prevented direct heating.

RESULTS AND PRELIMINARY DISCUSSION

Rates of surface temperature change (Table II)

Clean surfaces. When clean, all four stone types display similar light-coloured surfaces, but differences in thermal responses highlight the influence of other thermal properties as well as structural and mineralogical controls. Under warm air conditions (max. air temp. 40°C) all samples attain surface temperatures greater than those of the surrounding air. Baumberger sandstone and Portland limestone reach the highest surface temperatures and Baumberger displays the greatest surface temperature decrease during each 15 min shade period (Table IIa). This may reflect poor thermal conductivity and heat storage in surface layers from where it is rapidly lost once radiant energy is interrupted. Simultaneous surface/subsurface temperature measurements tend to support this explanation, as Baumberger sandstone experiences the greatest surface/subsurface temperature differences under warm air conditions (Table IIIa). Dunhouse sandstone and Pentellic marble exhibit comparable surface temperature characteristics under warm air conditions (Tables IIb and d).

When the cooling unit is activated, surface temperatures are reduced but tend to remain similar to, or slightly higher than, ambient air temperatures. Baumberger sandstone again displays the greatest surface temperature decrease during each 15 min shade period although Portland limestone experiences the highest surface temperatures.

Average rates of surface temperature change during each 15 min shade period for Dunhouse sandstone, Portland limestone and Pentellic marble are similar to those under warm air conditions. The rate of surface temperature change on Baumberger sandstone, however, is greater and possibly reflects increased surface heating of this particular sample. However, it is important to note that average rates of temperature change are not an accurate reflection of actual surface conditions. In all samples most surface temperature change occurs during the initial 5 min of shade. Rates of surface cooling then gradually decline as surface temperatures achieve equilibrium with cooler conditions (Table IIa–d).

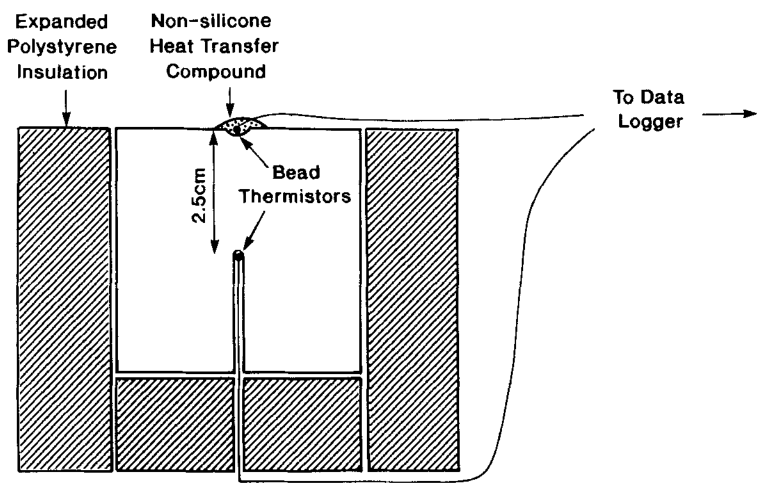


Figure 4. Insulated block and position of bead thermistors used in temperature measurement

Table II. Rates of surface temperature change (TC) for clean and soiled surfaces under warm and cool air conditions

		Surface temp. (°C)	TC after 1st 5 min (°C)	Rate of TC (°C/min)	TC after 2nd 5 min (°C)	Rate of TC (°C/min)	TC after 3rd 5 min (°C)	Rate of TC (°C/min)	Total TC (°C)	Average TC per 15 min cycle (°C/min)
(a) *Baumberger sandstone*										
	Clean surface	46·95	2·55	0·51	1·35	0·27	1·15	0·23	5·05	0·34
Warm air	Coal flyash	47·30	2·60	0·52	1·70	0·34	0·90	0·18	5·20	0·35
(30–40°C)	Oil flyash	55·05	3·55	0·71	2·70	0·54	1·30	0·26	7·55	0·50
	Clear surface	29·85	2·85	0·57	1·20	0·24	0·40	0·08	4·45	0·30
Cool air	Coal flyash	38·90	2·95	0·59	1·50	0·30	0·55	0·11	5·00	0·33
(20–30°C)	Oil flyash	38·45	4·30	0·86	1·80	0·86	0·60	0·12	6·70	0·45
(b) *Dunhouse sandstone*										
	Clean surface	45·45	1·55	0·31	1·00	0·20	0·60	0·12	3·15	0·21
Warm air	Coal flyash	52·70	2·65	0·53	1·40	0·28	0·90	0·18	4·95	0·33
(30–40°C)	Oil flyash	56·15	3·85	0·77	1·65	0·33	1·10	0·22	6·60	0·44
	Clean surface	27·70	1·70	0·34	0·60	0·12	0·15	0·03	2·45	0·16
Cool air	Coal flyash	32·60	3·05	0·61	1·10	0·22	0·45	0·09	4·60	0·31
(20–30°C)	Oil flyash	42·35	1·95	0·39	2·70	0·54	0·80	0·16	5·45	0·36
(c) *Portland limestone*										
	Clean surface	47·20	1·15	0·23	1·10	0·22	0·85	0·17	3·10	0·21
Warm air	Coal flyash	50·10	3·05	0·61	1·70	0·34	0·70	0·14	5·45	0·36
(30–40°C)	Oil flyash	62·95	4·85	0·97	2·35	0·47	3·15	0·63	10·35	0·69
	Clean surface	35·05	1·85	0·37	0·60	0·12	0·50	0·10	2·95	0·20
Cool air	Coal flyash	39·90	1·25	0·25	2·60	0·52	1·55	0·31	5·40	0·36
(20–30°C)	Oil flyash	49·15	5·00	1·00	2·55	0·51	1·00	0·20	8·55	0·57
(d) *Pentellic marble*										
	Clean surface	43·55	1·35	0·27	1·10	0·22	0·65	0·13	3·10	0·21
Warm air	Coal flyash	53·20	2·75	0·55	1·30	0·26	2·00	0·40	6·05	0·40
(30–40°)	Oil flyash	60·55	3·60	0·72	2·45	0·49	1·85	0·37	7·90	0·53
	Clean surface	29·65	1·45	0·29	0·60	0·12	0·35	0·07	2·40	0·16
Cool air	Coal flyash	41·50	3·10	0·62	0·85	0·17	0·90	0·18	4·85	0·32
(20–30°C)	Oil flyash	46·30	3·35	0·67	1·35	0·27	0·75	0·15	5·45	0·36

Soiled surfaces. Surface soiling with both coal or oil flyash increases surface temperatures of all stone types (Figures 5 and 6), particularly Portland limestone and Pentellic marble covered with oil flyash under warm and cool air conditions (Tables IIa and d). Under warm air conditions Portland limestone surface temperatures are > 30 per cent higher than for clean surfaces and rates of temperature change increased during each 15 min period from 0·21°C/min to 0·69°C/min (Table IIc and Figure 5c). Under cool air conditions soiling with oil flyash increases surface temperatures on Portland limestone by 40 per cent (Table IIc and Figure 6c).

In all cases surface soiling, especially with oil flyash, increases the magnitude of surface temperature change during each 15 min period. Under both warm and cool air conditions surface temperatures of Portland limestone decrease most rapidly when placed in shade, followed by Baumberger sandstone, Dunhouse sandstone and Pentellic marble. In all samples approximately 50 percent of total surface temperature decrease occurs during the first 5 min of shade. Surface soiling increases radiant energy absorption raising rock surface temperatures well above ambient air temperature and therefore, when receipt of radiant energy is interrupted, heat is rapidly lost from the rock surface to the cooler surrounding air. In general rock is a relatively poor conductor of thermal energy with the result that radiant energy absorbed tends to be stored in the outer few millimeters of rock from where it is rapidly lost, especially when ambient air temperatures are low.

Soiling therefore appears to affect surface temperatures in several ways.

(1) It raises surface temperatures under both warm and cool air conditions.
(2) It increases the rate of temperature decrease when incident radiant energy is interrupted.
(3) Through the combined effects of (1) and (2), soiling enhances the characteristically asymmetrical pattern of surface heating and cooling. Increased rates of heat loss/gain must in turn increase the magnitude of thermal stresses developed between individual, anisotropic mineral grains and between surface and subsurface parts of the stone.

Temperature changes with depth (Tables III)

Clean surfaces. Under both warm and cool air conditions Baumberger sandstone exhibits the largest simultaneous surface/subsurface temperature differences and highest average temperature gradient with depth (Table IIIa). This suggests that Baumberger sandstone does not readily conduct heat from surface to subsurface layers. Portland limestone displays the next steepest internal temperature gradients (Table IIIc), while data from Dunhouse sandstone and Pentellic marble suggest that thermal energy is more readily conducted from surface to subsurface layers and allows more uniform heating of these stones (Tables IIIb and d).

Soiled surfaces. Because soiling, especially with oil flyash, increases energy absorption and raises surface temperatures, it also increases surface/subsurface temperature gradients under both warm and cool air conditions. This is particularly evident for Baumberger sandstone and Portland limestone (Tables IIIa and c). Soiling (oil flyash) of Baumberger sandstone increases internal temperature gradients by approximately 70 and 90 per cent under warm and cool air conditions respectively. Similar soiling of Portland limestone increases differences in surface/subsurface temperatures by approximately 140 per cent under warm air conditions and 200 per cent under cool air conditions (Figures 5c and 6c).

Evidence suggests that surface soiling of light-coloured stone with a low thermal conductivity raises surface temperatures and increases surface/subsurface temperature gradients. Inevitably this must increase thermal stress between surface and subsurface layers, and must also affect microenvironmental conditions at the rock/air interface, increasing the complexity of interactions between weathering activity and stone response in this zone.

IMPLICATIONS

Measurements illustrate lithologically related temperature differences and clearly demonstrate the effects of changes in surface albedo. Soiling of light-coloured stone increases heat energy absorption and alters microenvironmental conditions at the rock/air interface. Such alteration has implications for the

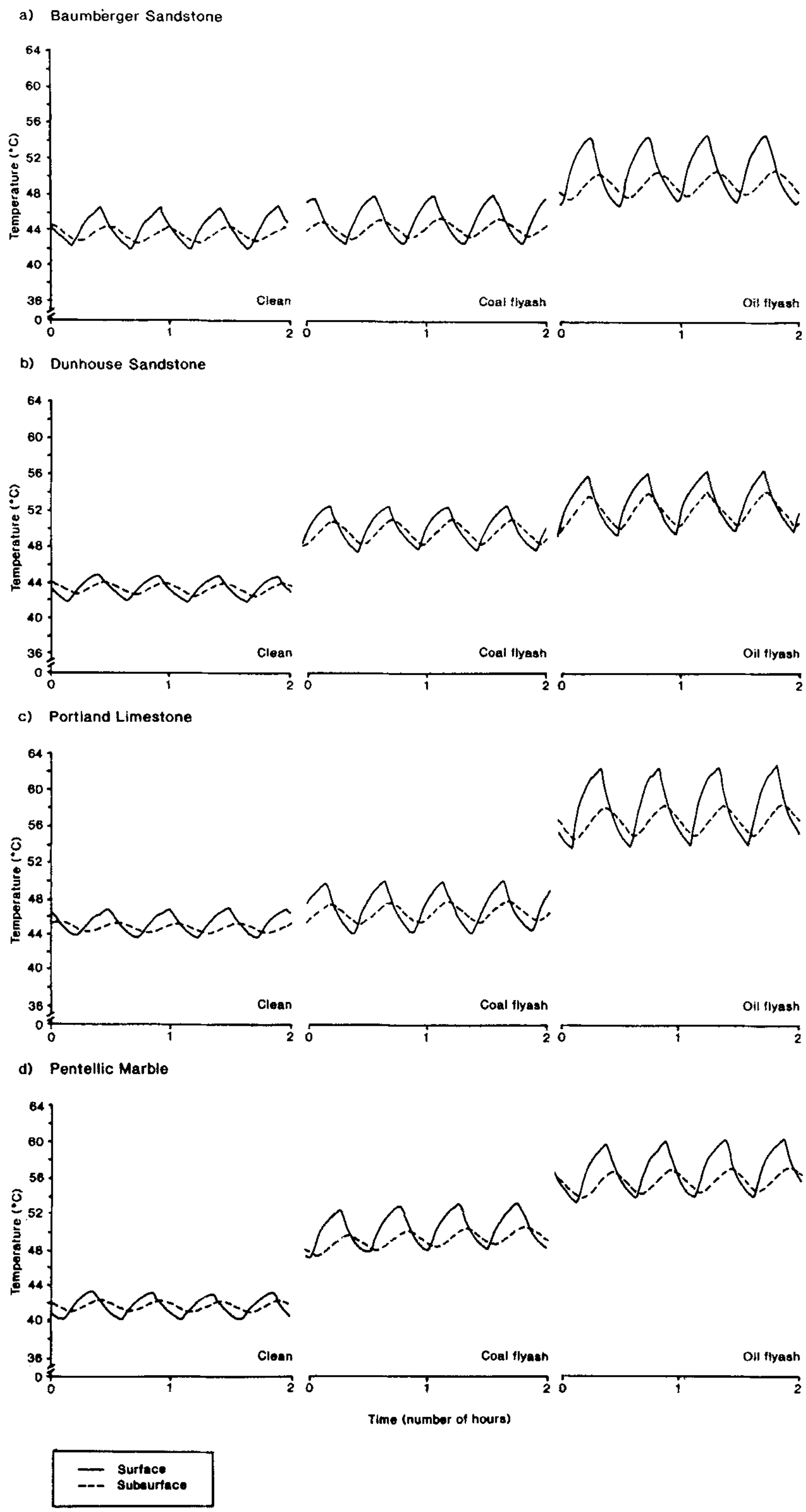


Figure 5. Surface and subsurface temperatures from insulated clean and soiled stone samples under warm air conditions

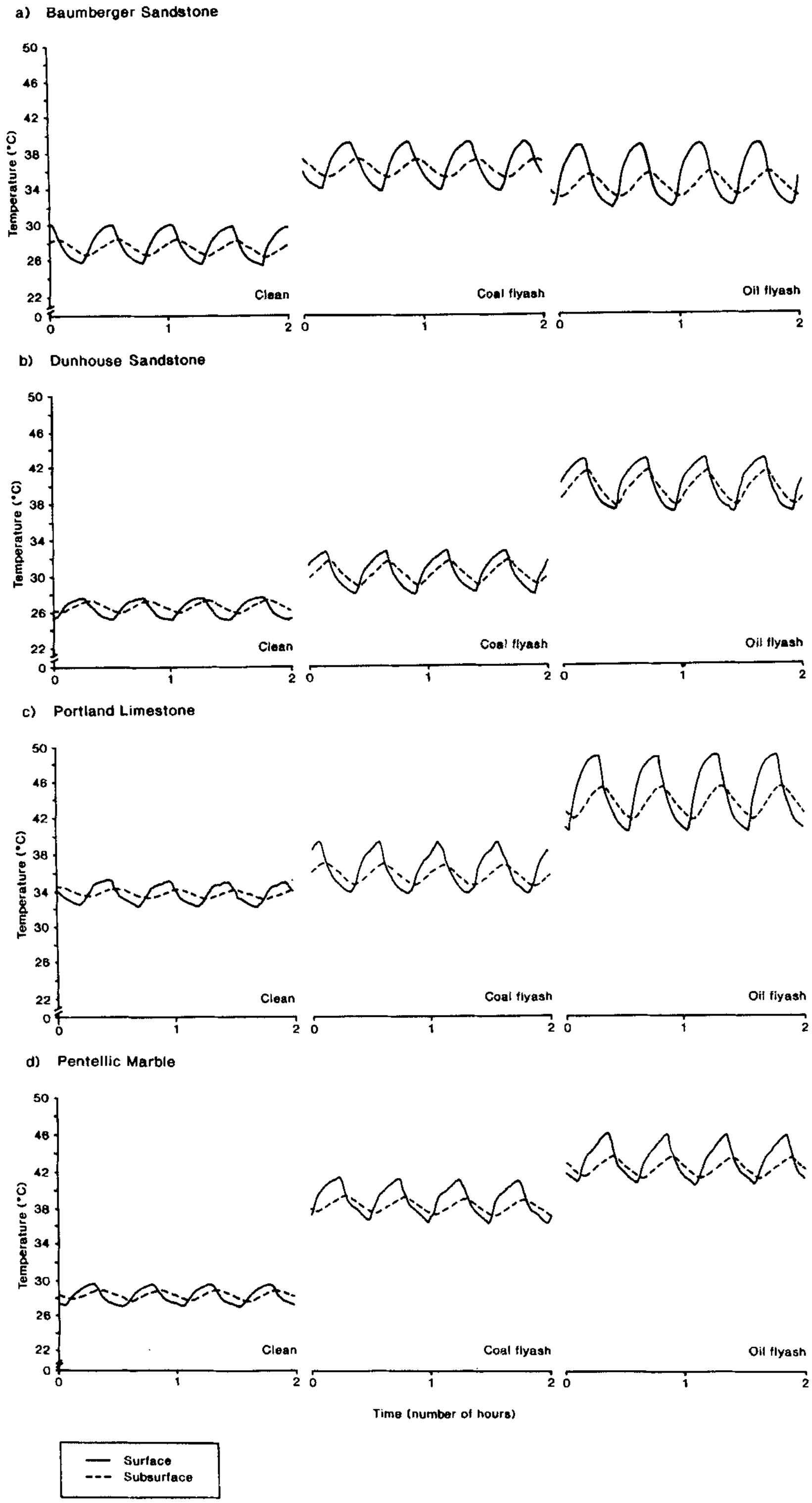


Figure 6. Surface and subsurface temperatures from insulated clean and soiled stone samples under cool air conditions

Table III. Rates of temperature change with depth on clean and soiled surfaces under warm and cool air conditions

		Max surface temp. (°C)	Simultaneous subsurface temp. (2·5 cm)	Diff. (°C)	Rate of decrease (°C/cm)	Min. surface temp. (°C)	Temp. range per cycle (°C)
(a) *Baumberger sandstone*							
	Clean surface	46·95	44·15	2·80	1·12	41·90	5·05
Warm air	Coal flyash	47·30	44·35	2·95	1·18	42·10	5·20
(30–40°C)	Oil flyash	55·05	50·30	4·75	1·90	47·50	7·55
	Clean surface	29·85	28·05	1·80	0·72	25·40	4·45
Cool air	Coal flyash	38·90	36·95	1·95	0·78	33·90	5·00
(20–30°C)	Oil flyash	38·45	35·00	3·45	1·38	31·75	6·70
(b) *Dunhouse sandstone*							
	Clean surface	45·45	44·35	1·10	0·44	42·30	3·15
Warm air	Coal flyash	52·70	50·95	1·75	0·70	47·75	4·95
(30–40°C)	Oil flyash	56·15	54·05	2·10	0·84	49·55	6·60
	Clean surface	27·70	27·30	0·40	0·16	25·25	2·45
Cool air	Coal flyash	32·60	31·45	1·15	0·46	28·00	4·60
(20–30°C)	Oil flyash	42·35	40·60	1·75	0·70	36·90	5·45
(c) *Portland limestone*							
	Clean surface	47·20	45·25	1·95	0·78	44·10	3·10
Warm air	Coal flyash	50·10	47·55	2·55	1·02	44·65	5·45
(40–30°C)	Oil flyash	62·95	58·20	4·75	1·90	52·60	10·35
	Clean surface	35·05	33·85	1·20	0·48	31·10	2·95
Cool air	Coal flyash	39·90	37·00	2·90	1·16	34·50	5·40
(21–30°C)	Oil flyash	49·15	45·35	3·80	1·52	40·60	8·55
(d) *Pentellic marble*							
	Clean surface	43·55	42·25	1·30	0·52	40·45	3·10
Warm air	Coal flyash	53·20	50·35	2·85	1·14	47·15	6·05
(30–40°)	Oil flyash	60·55	57·00	3·55	1·42	52·65	7·90
	Clean surface	29·65	28·85	0·80	0·32	27·25	2·40
Cool air	Coal flyash	41·50	39·10	2·40	0·96	36·65	4·85
(20–30°C)	Oil flyash	46·30	43·45	2·85	1·14	40·85	5·45

effectiveness of decay in this zone and hence for stone durability. For example, much urban stone decay is attributed to salt weathering. In urban environments salts may derive from a variety of sources such as sea spray, groundwater, de-icing agents, dust and from chemical reaction between derivatives of fossil fuel combustion and calcareous components of the stone itself. Most importantly, however, black gypsum crusts responsible for soiling can themselves act as reservoirs of salts that can be mobilized and moved into underlying stone by occasional rainwash or occult precipitation.

Evidence from laboratory simulation studies associates increased rates and extent of rock breakdown by salt crystallization and hydration pressures with extreme temperature conditions (Marschner, 1978; Price, 1978; Sperling and Cooke, 1985; Davison, 1986; Goudie, 1993). Moreover, a positive relationship has been shown to exist between crystallization pressures and temperature (Winkler and Singer, 1972; Sperling and Cooke, 1980), together with an associated tendency for salts to concentrate in the outer few millimetres of stone (Davison, 1986). In addition, the theoretical effectiveness of thermal expansion/contraction of near-surface interstitial salt deposits may be enhanced by increased stone surface temperatures although, as yet, this has not been conclusively demonstrated under 'natural' conditions. Raised surface temperatures also have implications for the efficacy of chemical reactions, and high rock surface temperatures are highlighted as a significant factor in enhancing chemical decay (Whalley, 1984; Whalley *et al.*, 1984; McGreevy, 1985).

Although average rates of temperature decrease with depth have been used to illustrate lithological differences, they probably do not provide an accurate reflection of actual cooling patterns. Smith (1977) observed that the surface/subsurface thermal gradient is not uniform and that greatest rates of temperature decrease occur in the outer few millimetres of rock. Large surface/subsurface temperature gradients may give rise to more severe thermal stresses in this region than average rates of temperature decrease with depth would otherwise indicate. Results suggest that this asymmetry is enhanced by soiling, particularly in Baumberger sandstone and Portland limestone.

The significance of rapid temperature change lies in the fact that the thermal stresses established may be of sufficient magnitude and occur sufficiently frequently to promote microfracturing of surface grains (Yatsu, 1988). This is of particular relevance to lithologies which comprise a variety of minerals with different thermoelastic properties, but also has implications for homogeneous rock types, such as marble, where grain orientation is variable. The response of calcite, for example, to thermal stress is direction-dependent because it is an anisotropic mineral. When the temperature of an unconfined calcite crystal is raised by 30°C it expands linearly by 0·075 per cent along the optic axis while contracting by 0·015 per cent in the perpendicular directions with a net volume increase of 0.045 per cent (Lewin, 1990). When calcite grains are packed together, individual grains are unable to expand parallel to their optic axis and internal pressures develop compressing the crystal by the 0.045 per cent that it would otherwise have expanded by. In this study surface soiling with oil flyash raised marble and limestone temperatures to over 60°C under warm air conditions, increasing intergranular stresses between individual heated surface grains and between these and cooler subsurface material. Although the stresses involved are small in comparison to the compressive strength of marble (Touloukian *et al.*, 1989) repetition of these low magnitude, high frequency stress events may eventually give rise to a 'fatigue' effect by gradually reducing the cohesive strength of intergranular bonds and initiating microfracture development. Aires-Barros *et al.* (1975) have shown that detectable surface change (microfracture initiation and propagation) can occur as a result of repeated short-term heating and cooling of rock samples and if rates of temperature change are sufficiently rapid ($\geq$ 2°C/min) microfracture development will be enhanced (Richter and Simmons, 1974). Although repeated low magnitude heating and cooling of rock has not been shown to cause catastrophic rock breakdown, its importance as a potential weathering mechanism lies in the microscale changes initiated (intra- and intergranular microfracturing). These microscale 'fatigue' effects may contribute indirectly to rock breakdown by facilitating the ingress, and enhancing the effectiveness, of exploitative weathering agents such as salt and moisture.

Results presented highlight the importance of albedo in determining the thermal response characteristics of stone to direct heating under laboratory conditions. Much scope remains for the collection of microenvironmental data from 'soiled' and 'clean' stone surfaces under 'real' conditions with further simulation study of the effects of changes in microenvironmental controls on weathering effectiveness on fresh and previously weathered stone.

Thus, while macroenvironmental climate may be indicative of relatively temperate conditions, microenvironmental parameters may be much more extreme. Consequently, the nature of decay processes active at the rock/air interface may be different and their effectiveness greater than comparatively moderate macroenvironmental conditions suggest. Finally, these findings, therefore, present an additional element in the argument as to whether features such as black crusts should be removed from buildings. Previous arguments have centred around questions of aesthetics, historical integrity, cost and the need for consolidation of cleaned stone (Maxwell, 1992). This study suggests that, for some stones, removal of crusts and other dark surface stains could at least reduce the degree of physical stressing that they experience as a result of environmental temperature fluctuations.

In 'natural' environments, especially hot deserts, the effect of albedo change may also be an important factor in stone weathering and breakdown. Large parts of these areas comprise bare rock surfaces exposed to prolonged periods of insolation and, frequently, high temperature conditions. In such environments albedo change can result from rock varnish and weathering rind development, iron staining and algal and lichen growth. Although causes of albedo change may differ from those in urban environments, the overall effect should be the same, surface energy absorption will be increased and more extreme temperature conditions produced at the rock/air interface.

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REFERENCES

Aires-Barros, L., Graça, R. C. and Velez, A. 1975. 'Dry and wet laboratory tests and thermal fatigue of rocks', *Engineering Geology*, **9**, 249–265.

Davison, A. P. 1986. 'An investigation into the relationship between salt weathering debris production and temperature', *Earth Surface Processes and Landforms*, **11**, 335–341.

Goudie, A. S. 1993. 'Salt weathering simulation using a single immersion technique', *Earth Surface Processes and Landforms*, **18**, 369–376.

Hall, K. and Hall, A. 1991. 'Thermal gradients and rock weathering at low temperatures: some simulation data', *Permafrost and Periglacial Processes*, **2**, 103–112.

Jenkins, K. and Smith, B. J. 1990. 'Daytime rock surface temperature variability and its implications for mechanical rock weathering: Tenerife, Canary Islands', *Catena*, **17**, 449–459.

Leary, E. 1986. *The Building Sandstones of the British Isles*, Building Research Establishment Report, Department of the Environment Building Research Establishment, HMSO, London.

Lewin, S. 1990. 'Susceptibility of calcareous stones to salt weathering,' Zezza, F. (Ed.), *Proceedings of 1st International Symposium, Conference on Conservation of Monuments in the Mediterranean Basin*, Bari, Italy, 59–63.

Marschner, H. 1978. 'Application of salt crystallisation test to impregnated stones,' *RILEM/UNESCO Symposium*, Paris, Report **3.4**.

Maxwell, I. 1992. 'Stone cleaning – for better or worse? An overview,' in, Webster, R. G. M. (Ed.), *Stone Cleaning and the Nature, Soiling and Decay Mechanisms of Stone*, Donhead Publishing, London, 3–49.

McGreevy, J. P. 1982. *Some field and laboratory investigations of rock weathering, with particular reference to frost shattering and salt weathering*, Unpublished PhD Thesis, The Queen's University of Belfast.

McGreevy, J. P. 1985. 'Thermal properties as controls on rock surface temperature maxima and possible implications for rock weathering', *Earth Surface Processes and Landforms*, **10**, 125–136.

Price, C. A. 1978. 'The use of the sodium sulphate crystallisation test for determining the weathering resistance of untreated stone', *RILEM/UNESCO Symposium*, Paris, Report **3.6**.

Richter, D. and Simmons, G. 1974. 'Thermal expansion behaviour of igneous rocks', *International Journal of Rock Mechanics and Mining Science and Geomechanics Abstracts*, **11**, 403–411.

Sabbioni, C., Zappia, G., Pauri, G. and Gobbi, G. 1992. *Environmental deterioration and protection of historic buildings. Summary of the main results obtained during the first year period*, Unpublished STEP Report, Contract STEP CT90 0107.

Smith, B. J. 1977. 'Rock temperature measurements from the northwest Sahara and their implications for rock weathering', *Catena*, **4**, 41–63.

Smith, B. J. and Magee, W. R. 1990. 'Granite weathering in an urban environment: an example from Rio de Janeiro', *Singapore Journal of Tropical Geography*, **2**(2), 143–153.

Sperling, C.H.B. and Cooke, R.U. 1980. *Salt weathering in arid environments I. Theoretical considerations*, Papers in Geography No. **8**, Bedford College, University of London.

Sperling, C. H. B. and Cooke, R. U. 1985. 'Laboratory simulation of rock weathering by salt crystallisation and hydration processes in hot arid environments', *Earth Surface Processes and Landforms*, **10**, 541–555.

Touloukian, Y. S., Judd, W. E. and Roy, R. G. 1989. *Physical Properties of Rocks and Minerals*, McGraw-Hill, New York,

Whalley, W. B. 1984. 'High altitude rock weathering processes', in Miller, K. J. (Ed.), *The International Karakoram Project, Vol. 1*, Cambridge University Press, Cambridge, 365–373.

Whalley, W. B., McGreevy, J. P. and Ferguson, R. I. 1984. 'Rock temperature observations and chemical weathering in the Hunza region, Karakoram: preliminary data', in Miller, K. J. (Ed.) *The International Karakoram Project. Vol. 2*, Cambridge University Press, Cambridge, 616–633.

Whalley, W. B., Smith, B. J. and Magee, R. W. 1992. 'Effects of particulate air pollutants on materials: investigation of surface crust formation', in Webster, R.G.M. (Ed.), *Stone Cleaning and the Nature, Soiling and Decay Mechanisms of Stone*, Donhead Publishing, London, 227–234.

Winkler, E. M. and Singer, P. C. 1972. 'Crystallisation pressure of salts in stone and concrete', *Geological Society of America Bulletin*, **83**, 3509–3514.

Yatsu, E. 1988. *The Nature of Weathering*, Sozosha, Tokyo. 624 pp.